2nd Micro and Nano Flows Conference
West London, UK, 1-2 September 2009

Analysis of the topography of microchannels with different sizes

Andrea LUKE, Hannes STRÜBING, Björn C.F. MÜLLER

- Corresponding author: Tel.: +49 (0)511 762 2277; Fax: +49 (0)511 7623857;
Email: luke@ift.uni-hannover.de

Institute for Thermodynamics, Leibniz University Hanover, GERMANY

Abstract: The longterm aim in the design of modern evaporators is to find a heat transfer calculation method based on the phenomena of growing and departing vapour bubbles on the heated surface. New developments in computer calculation and in measurement technique support the local analysis of the heat transfer, bubble formation and the microstructure of the heated surface. All three kinds of data originate from the same equipment and from experiments performed with equal detail and precision.
The influence of different rough and structured surfaces on the heat transfer coefficient will be investigated by a joint research project of Brunel and Hannover Universities with refrigerants boiling in single microchannels of different inner diameter. The microchannels are capillary tubes and they are manufactured by industrial processes. The samples of the microchannels have to be prepared by special methods, because the surfaces inside the microchannels cannot be measured in the same way as used for the heat transfer measurements. The microstructure of the surfaces of three microchannels (D = 0.4, 0.5 and 0.8mm) is measured by a contact stylus instrument. The paper will focus on the detailed description of the profiles and the topographies of the samples. The roughness parameter in accordance with standard practice are calculated for ca 1000 runs (profiles). The roughness parameters of the smaller microchannels are twofold higher than those of the largest microchannel investigated. The scattering of the roughness of the largest microchannel (D = 0.8 mm) is less and the cavities are smaller than those of the other ones (D = 0.4 and 0.5 mm). All surfaces investigated demonstrate a deterministic microstructure as for emery ground surfaces on smooth tubes in the literature.

keywords: surface roughness, microchannel, topography, surface analysis

1. Introduction

Heat exchangers are becoming increasingly miniaturized to save energy and to conserve natural resources. High heat flux densities can be transferred by small temperature gradients in evaporators. This high transfer capability is now used even in fields, where two phase systems were avoided by reason of their complexity. New prediction methods for heat and mass transfer in pool and flow boiling will be therefore required in future to succeed the empirical correlations used until now. The calculation methods for the design of evaporators are based on more or less accurate heat transfer measurements. They are often not attended by equally accurate studies of the roughness of the heated surface and of the bubble formation, data for a large pressure range are especially rare in the literature.

Flow boiling experiments in vertical microchannels are performed with refrigerants as liquid in a joint research project with Brunel University, Shirew et al. (2007). The boiling experiments are carried out at Brunel with a recently modified test rig, see Huo (2005). In order to provide experimental material that meets the above mentioned criteria, roughness measurements within different microchannels have recently been started, because data for such are often not available in the literature. The surface roughness of the microstructure of three microchannels with different diameter (0.4, 0.5, 0.8mm) is studied by means of a stylus instrument. To investigate the surface topography inside a microchannel, a special preparation method of the samples is developed. The measurement and evaluation technique of the surface topography are described and the results are discussed.

2. Preparation method

The microchannels are capillary tubes made of stainless steel. The microstructure of interest is the inner surface of the microchannels. Investigations on the original heated surface are therefore not possible. Samples for the roughness measurements have to be carefully prepared without destroying the inner surface. The samples are sections of a capillary endless material which is winded in coils after production. The material is bended because of the winding process and caused a curvature of the topography, see Chapter 3. This bending should be as small as possible and without macroscopic deformation for the roughness measurements to analyse a gauge length of the profile of a reasonable size.

Therefore, several preparation methods are developed and tested. Especially the methods

- cutting by laser,
- negative copy and
- cutting by conventional mechanic tools

offer a high potential in efficiency and quality for which reason these methods have to be developed in future.

The laser cutting is not possible in this case because of the large curvature in consequence of the small diameter. Because of the evaporation process by the high temperature of the procedure, small material particles are deposited on the surface inside the tube and would destroy the surface to be investigated.

The negative copy method seems to be very appropriate for the future. In this case special silicon is pressed into the capillary tubes and build up a negative form of the inside roughness topography of the wall. For this paper, this idea could not be realized because the needed vacuum chamber is not available. Therefore, the mechanically cutting procedure is used in the following.

First, the small pieces of the capillary tubes are embedded in epoxy for a better handling of the small pieces during the cutting and measurements, see Figure 1. Three different sizes of the capillary tubes are investigated (the inner diameter is D = 0.4, 0.5, 0.8mm), see Figure 1.

Figure 1: Alloy casting mould for the epoxy with sections of the microchannels with different diameter (I.D. from 0.4 m, 0.5 mm and 0.8 mm)

The endless spooled capillary tube is cut in several small samples of 20 mm. The channels are closed at the ends by the cutting process so that no material may enter into the channels to destroy the original surface of the microchannel within the tube. The small samples are fixed in an alloy form and then embedded in a two component epoxy. The alloy form is resistant to the high reaction temperature of the two-component resin and may be used several times to prepare the samples of different microchannels with varying diameter, see Figure 1.

The alloy forms filled with epoxy are exposed on a milling machine for the subsequent splitting of the capillaries. The aim of this procedure is to cut the microchannels to investigate the wall surface roughness inside the channels. The epoxy should support the wall of the microchannel during the cutting process. Since the thin walls of the channels are damaged in contact with the forehead by a 6mm cutter, despite of the embedding epoxy, the further preparation is carried out with a very low depth of cut of 20 µm and a forward feed of 10 µm.

The measurement instrument for the surface roughness (see Chapter 3) needs a resisting channel height of about 0.1 to 0.2 mm, otherwise the stylus would touch the remains of the epoxy and the stylus is not able to reach the bottom of the channel. The last milling step uses only a 1 µm depth of cut to smooth the edges. Additionally, the epoxy has to be removed carefully at the outside of the channel walls. The embedded and exposed samples are cleaned intensively by 2-propanol. The prepared sample of the microchannels with a diameter of D = 0.4mm ready for roughness measurements is shown in Figure 2.

3. Surface Analysis

Different measurement techniques are established for the characterization of the surface roughness or microstructure of heating elements, see Luke (2006). Stylus based measurement instruments are often used for the quantitative description of the microstructure, because the method is easy to apply and a number of various roughness parameters is standardized especially for manufacturing

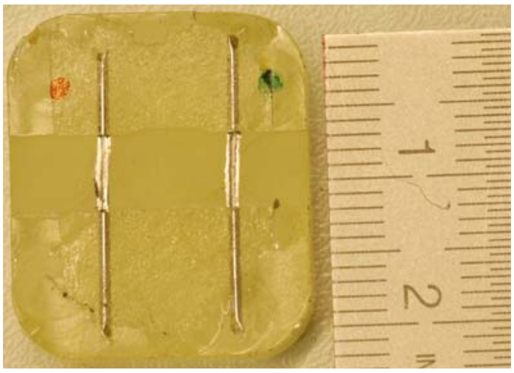

Figure 2: Microchannels of I.D. 0.4 mm embedded in epoxy after the milling and cutting process ready for the roughness measurements

reasons (Luke, 2006). Some of these roughness parameters – R_a or R_p – are integrated within the calculation method for the heat transfer in pool boiling, see Gorenflo (2006), Cooper (1984) and flow boiling, see Steiner (2006) or Steiner and Taborek (1992).

The main problem in concentrating on one single integral roughness parameter is that this analysis limits our idea of technical rough surfaces because they usually are more or less anisotropic. The complete understanding of the links between surface microstructure and evaporating process has to be realized by considering the distribution of the roughness parameter, by a three-dimensional approach to surface characterization and by the wetting conditions of the microstructure by the boiling and flowing fluid at different saturation conditions within capillary tubes.

The microchannels are analyzed by a contact stylus instrument, see Luke (1997), Luke (2006). The tip is driven slowly over the surface by special forward feeds. The movements of the tip correspond to the surface roughness, they are digitalized and amplified. In this case, the contactless stylus is not used. Some of the sharp edges at the channel wall may cause a irreversible damage of the very sensible ultrasonic stylus system. The diamond tip of the stylus has the radius of 2 µm and the angle of 60°. The restricting geometry of the stylus tip has to be considered, see the qualitative profile of a conventional stylus tip with 5µm and 90° angle in Figure 3, bottom. Narrow and deep channels with steep edges lead to deviations of the measured differences in height and in inclination of the angles.

The measurement chain is also represented in Figure 3, top. Macrostructures up to a magnitude of ± 800 µm may be analyzed, therefore the channel walls has to be reduced in their size (see the chapter before). The inaccuracies of the measuring chains result in at most 0.6 % of the standardized roughness parameters (linear advance and stylus system with 2 nm).

One scan represents a conventional roughness profile (see the qualitative representation in Figure 3, bottom and the measured profile of the smallest diameter investigated in Figure 4, top), where the standard parameters acc. to DIN EN ISO 4287(10.98) are applied. The gauge length is reduced compared to the standard and is even smaller than used for smooth tubes, see Luke and Müller (2009), because of the very small diameter of the minichannels. The same method as for investigations in macrocavities is applied, see Luke (2006). The profiles are taken in the radial direction of the channel describing the main roughness, see Figure 4. The original profiles as in Figure 4, top, are recalculated to separate the real roughness profile from the waviness and form deviation, compare the profile in figure 4 with those of Figure 5 in the next chapter.

Precise forward feeds in axial y-direction provide ca 1000 single scans with a very small distance of $\Delta y = 0.5$ µm for topographies (quasi 3-dimensional measurements). The profile departure is provided with a resolution of $\Delta z = 10$ nm for each profile. The topographies are investigated over a differing number of locations within the microchannels. The original microchannels are not even and strict, so that a curverture within the topographies is observed, see Figure 4.

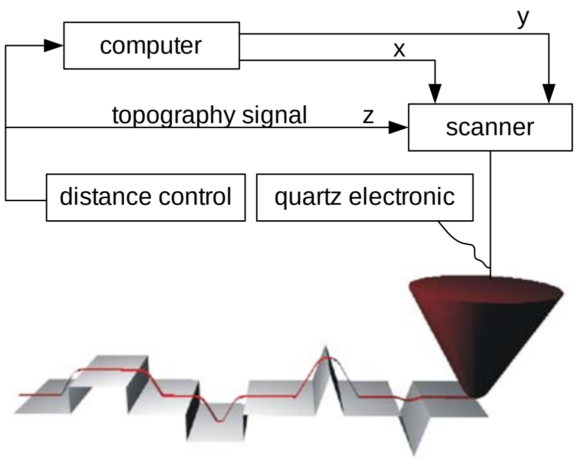

Figure 3: Visualization of the measurement chain and the principle of the contact stylus instrument

Evaluation programmes enable the isometrical (middle) and photorealistical (bottom) representation of the topography in Fig. 4, (as example of such quasi three-dimensional measurements serves the microchannel with D = 0.4 mm and P_a = 1.91 µm). The transferred data serve as x-y-z data of the topography from which further calculation methods may be developed.

4. Results of the Surface Analysis

The originally measured topography with the parts of the polished epoxy is shown in Figure 4. The bending in consequence of the rolling process is visualised by the photorealistical and isometrical representation, see Figure 4, middle and bottom. For the investigation of the standardized roughness parameters, the waviness of the profile evoked by the channel diameter has to be removed. The form deviation, the waviness and the epoxy surface is separated by special calculation procedures to receive the rough microstructure of the bottom of the microchannel.

The results of these calculation procedures are shown in Figure 5 for the profiles of each microchannel investigated and in Figure 6 for the topographies. The gauge length is different for the three surfaces because of the different diameter of the microchannels, see Figure 5 and 6. The results for the roughness parameter P_i according to Standarad DIN EN ISO 4287 (1998) for the 2-dimensional profiles as in Figure 5 are listed in Table 1 and in addition the 3-dimensional parameter according to Stout et al. (1993) for the topographies. The 2-dimensional standardized roughness parameters P_i have equivalent counterparts in 3-dimensional characterization S_i.

The topography of the microchannel with the smallest diameter (D = 0.4mm), see Figure 6, top, demonstrates grooves as emery ground copper and steel surfaces, cf also Luke (2004). The grooves for the larger diameters are not so pronounced, see Figure 6, bottom.

The standardized roughness parameters results in values higher than for emery copper or steel surfaces, see Table 1 and Luke (2004). The standard roughness parameter are the highest for the microchannel with D = 0.5 mm. The smallest values are registered in the case of the largest microchannel (D = 0.8mm) with P_a = 0.76 µm ca. twice of the typical values of emery ground copper surfaces of smooth tubes (P_a = 0.4 µm according to Gorenflo, 2006) and nearly the half of the value of the channels with the smaller diameters (1.4µm, or 1.2 µm, resp.).

Nevertheless, the different gauge length for the profiles investigated may be considered. By reducing the gauge length of the emery ground surfaces in Table 2 the results differ

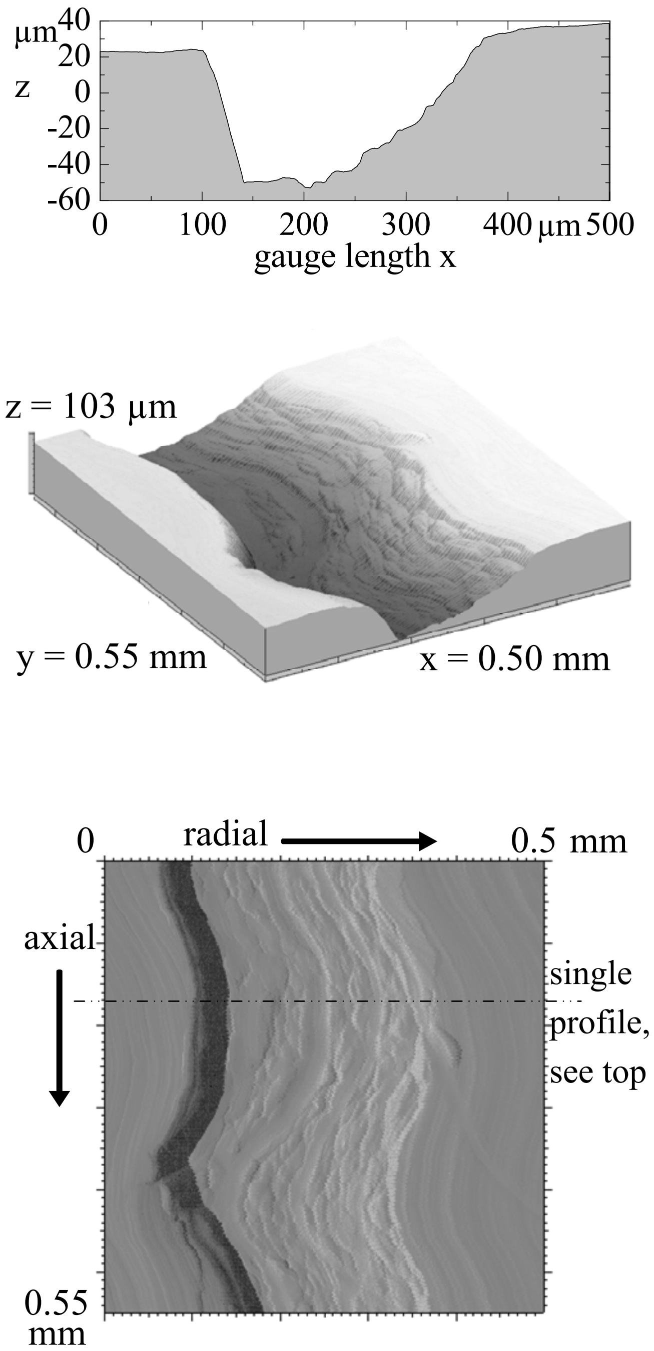

Figure 4: Measured profile (top) and isometrical visualization (middle) of the microchannel MC04 (D = 0.4 mm) and the photorealistical representation (bottom)

less than might be assumed. The topographies in Luke (2004) are reinvestigated and recalculated for the smaller gauge length of 0.25 mm. The results of the integral roughness parameter P_a and P_q do not vary with decreasing gauge length, while the roughness parameter representing single effects within the profile as P_p and P_t are more or less different, as Table 2 shows.

The same holds for the shorter gauge length for the largest microchannel (D = 0.8 mm). The integral value P_a is still the smallest value compared to the values for microchannels of D = 0.5 and 0.4 mm. *Therefore, the results demonstrate the effect of the manufacturing process on the roughness of the microchannel.*

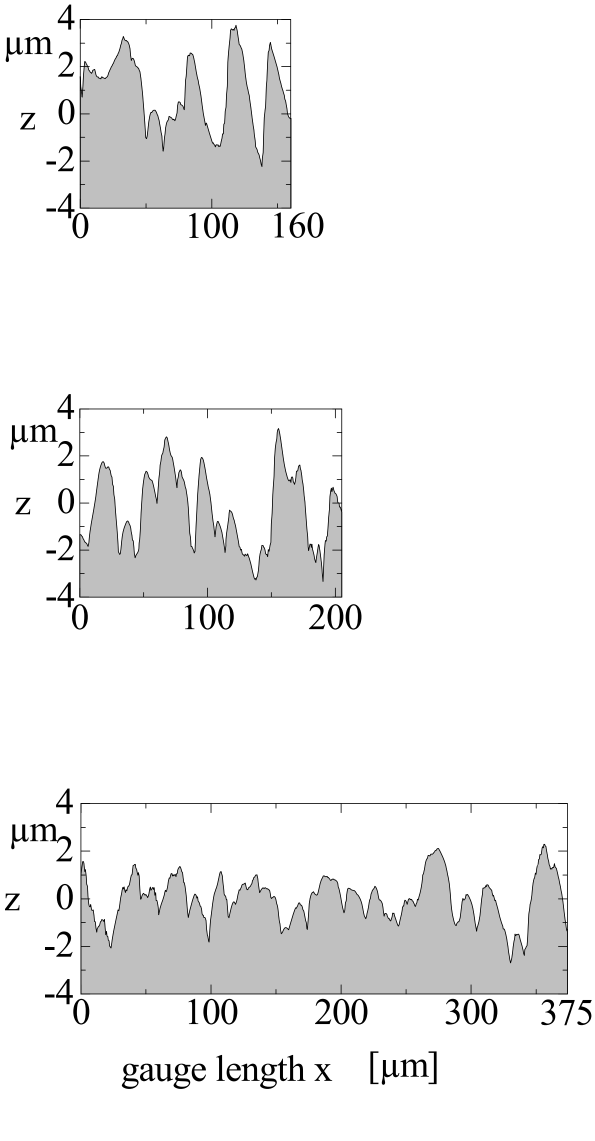

Figure 5: Representative profiles of the microchannels with different diameter (D = 0.4 mm, top, D = 0.5 mm, middle, D = 0.8 mm, bottom). Enlargement: z/x= 6

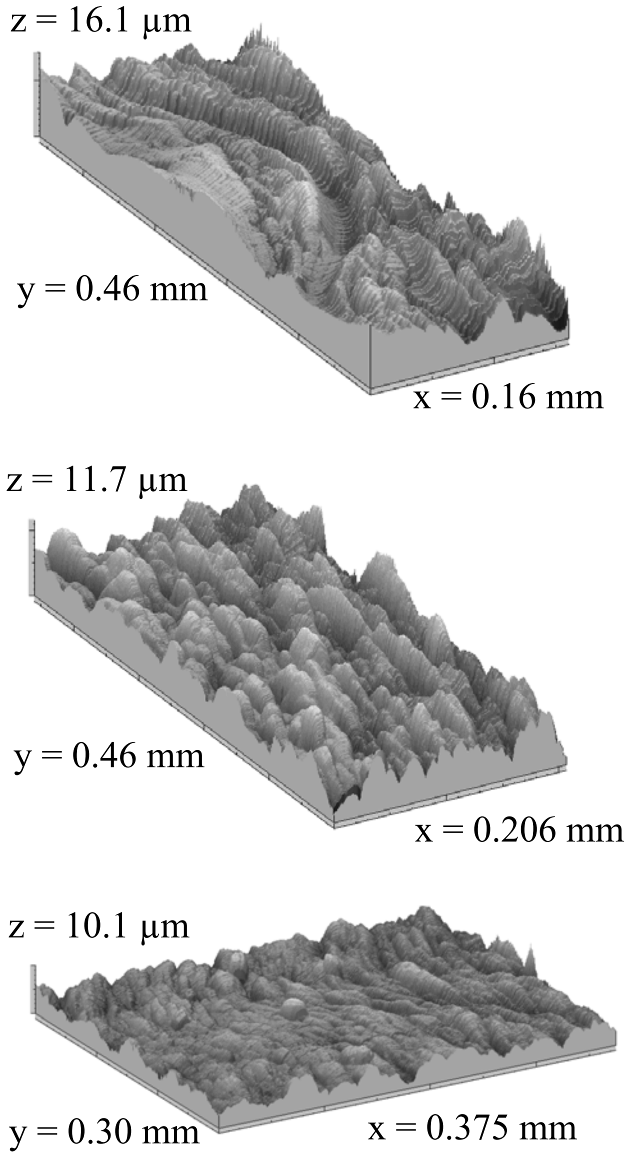

Figure 6: Representative topographies of the microchannels with different diameter (D = 0.4 mm, top, D = 0.5 mm, middle, D = 0.8 mm, bottom). Enlargement: z/x = 4

Table 1: Roughness parameters of the microchannels acc. to DIN EN ISO 4287 (10.98) with the varying gauge length of x, without cut-off ($\lambda_c = \infty$)

Diameter (code number) Treatment		Gauge length x [mm]	P_a [µm]	P_q [µm]	P_p [µm]	P_{pm} [µm]	P_t [µm]	P_z [µm]	runs
I.D. = 0.4 mm stainless steel MC04	average	0.160	1.19	1.47	3.14	2.05	6.33	4.11	922
	max.		2.01	2.33	5.52	3.91	8.71	7.05	
	min.		0.72	0.87	1.64	1.20	3.60	2.51	
	σ		0.26	0.30	0.77	0.56	1.08	0.82	
	S_i 1)		1.45	1.79	6.96		15.10	11.20	
I.D. = 0.5mm stainless steel MC05	average	0.206	1.41	1.71	3.90	2.48	7.76	5.24	920
	max.		1.91	2.22	6.02	3.53	10.98	6.72	
	min.		0.97	1.17	2.35	1.69	5.18	3.90	
	σ		0.19	0.21	0.73	0.37	1.10	0.59	
	S_i 1)		1.47	1.80	6.07		11.70	10.70	
I.D. = 0.8 mm stainless steel MC08	average	0.375	0.76	0.96	2.60	1.82	5.10	3.69	599
	max.		1.02	1.30	6.19	3.28	8.70	5.40	
	min.		0.60	0.74	1.48	1.28	3.40	2.96	
	σ		0.07	0.10	0.76	0.34	0.86	0.40	
	S_i 1)		0.78	0.99	5.98		10.10	7.42	

Table 2: Roughness parameters of the microchannel with D = 0.8mm and emery ground surfaces of the literature (Luke, 2004) acc. to DIN EN ISO 4287 (10.98) with the reduced gauge length of x

Diameter (code number) Treatment		Gauge length x [mm]	P_a [µm]	P_q [µm]	P_p [µm]	P_{pm} [µm]	P_t [µm]	P_z [µm]	runs
I.D. = 0.8 mm stainless steel MC08	average	0.180	0.74	0.93	2.18	4.38	2.73	1.28	599
D = 8.04 mm copper, emery ground #400 R18G1	average	0.250	0.53	0.72	1.80	4.56	2.59	1.25	1067
	average	0.500	0.53	0.69	1.82	4.74	3.05	1.36	
D = 30.00 mm mild steel, emery ground #400 DS9G	average	0.250	0.14	0.18	0.50	0.98	0.64	0.30	1001
	average	0.500	0.16	0.20	0.59	1.17	0.84	0.41	
D = 15.00 mm stainless steel, emery ground #400 DSSG2	average	0.250	0.16	0.21	0.62	1.38	1.02	0.51	501
	average	0.500	0.17	0.22	0.70	1.63	1.20	0.57	

Finally, the fluctuations of the standardized roughness parameter are shown in Figure 7 and Figure 8. For each scan of the topography in Figure 6, the integral roughness parameter P_a is calculated. The scattering of P_a of the smaller microchannels is similar, see Figure 7, top, while the smoother surface of the larger diameter (D = 0.8 mm) shows smaller scatter with nearly the half of the standard deviation of the surfaces of the smaller capillary tubes.

The probability distribution of the P_a -values for the three surfaces investigated are represented in Figure 8. The very small and regular distribution of the largest diameter in Figure 8, bottom, differ from the other more irregular distributions (Figure 8).

The broadest distribution is shown for the smallest diameter, where values larger than P_a = 2.0 µm are calculated and values smaller than P_a = 0.75µm (the mean values for the D = 0.8mm capillary tube).

The scatter would result in an augmentation of the heat transfer of 15% according to Gorenflo (2006) for pool boiling. The effect of the surface roughness on flow boiling heat transfer is less, although for boiling within microchannels the influence increase with decreasing sizes of the channels. In this case, the complicate relation of surface roughness, wettability and thermophysical properties of the boiling liquid has to be considered and is still not known.

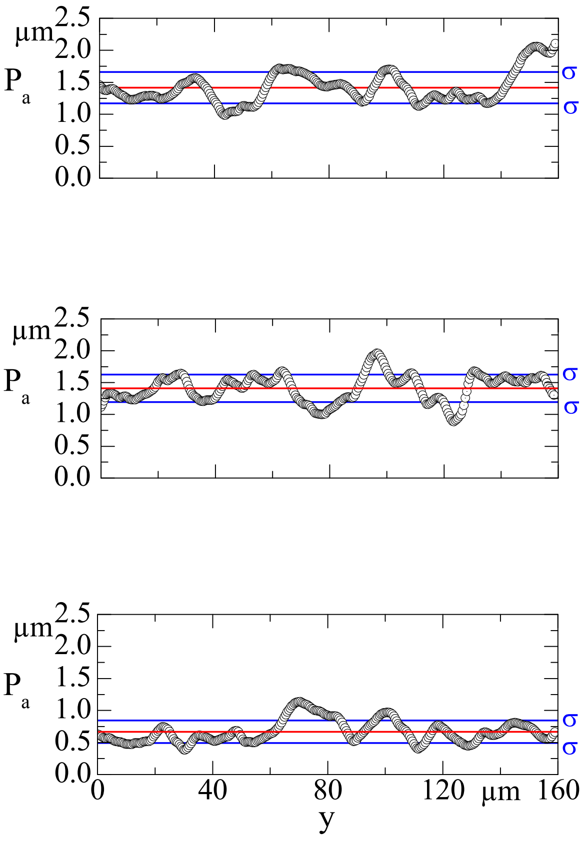

Figure 7: Average mean roughness $P_a(y)$ in axial direction of the microchannels with different diameter 0.4 mm (top), 0.5 mm (middle), 0.8 mm (bottom) according to profiles in Figure 5

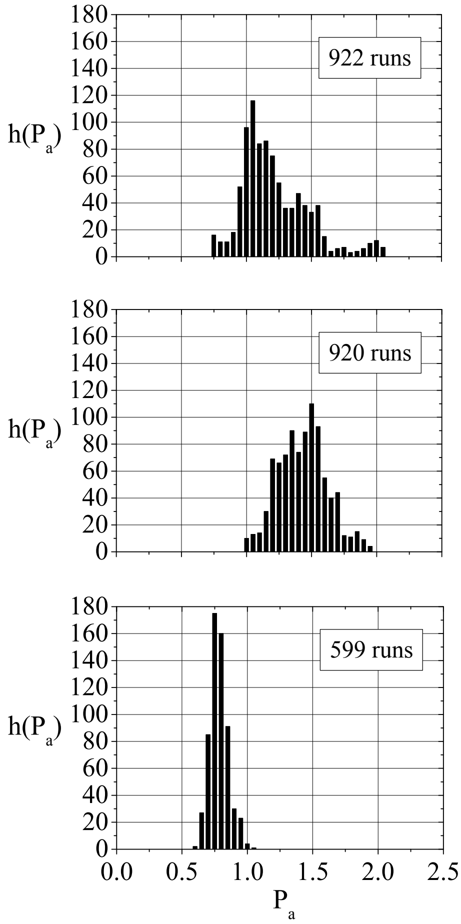

Figure 8: Probability distribution of the P_a values of the microchannels with different diameter 0.4 mm (top), 0.5 mm (middle), 0.8 mm (bottom)

5. Conclusions

The microstructure of microchannels with three different inner diameters is investigated for flow boiling experiments with refrigerants in a joint research project. Special preparation procedures are developed and the analysis according to standard show that the smaller microchannels demonstrate roughness parameters twice as high as the largest microchannel investigated (D = 0.8 mm). This is also demonstrated by the 2-dimensional profiles and the 3-dimensional topographies.

In future, the x,y,z-data resulting from the topography measurements serves for a detailed statistical analysis of the size, form and distribution of the cavities within the microstructure to establish a link to the boiling process and the bubble formation within the capillary tubes.

6. Reference

Cooper, M.G., 1984. Heat flow rates in saturated nucleate pool boiling – a wide ranging examination using reduced properties. Advances in Heat Transfer. 16, 157–239.

Gorenflo, D., 1993. Behältersieden. Abschnitt Hab, VDI-Wärmeatlas, 10th ed. Springer-Verlag, Berlin 2006. cf also: Pool boiling. Chapt. Ha. VDI-Heat Atlas, VDI-Verlag, Düsseldorf.

Huo, X., 2005. Experimental study of flow boiling heat transfer in small diameter tubes. PhD Thesis, London South Bank University.

Luke, A., 1997. Pool boiling heat transfer from horizontal tubes with different surface roughness. Int. J. Refrig. 20, 561-574.

Luke, A., 2004. Active and Potential Bubble Nucleation Sites on Different Structured Heated Surfaces. Chem. Eng. Research and Design. 82, 462–470.

Luke, A., 2006. Preparation, measurement and analysis of the microstructure of evaporator surfaces. Int. Journal of Thermal Sci. 45, 237-256.

Luke, A., Müller, B.C.F., 2009. Nucleate Boiling of Natural Refrigerants in a wide Pressure Range. Proc. 7th Experimental Heat Transfer, Fluid Mechanics and Thermodynamics (ExHFT), Krakow (Poland).

Shiferaw, D., Karayiannis, T.G., Kenning, D.B.R., 2007. Examination of heat transfer correlations and a model for flow boiling of R134A in small diameter tubes. International Journal of Heat and Mass Transfer, Vol. 50, 5177-5193.

Steiner, D., Taborek, J., 1992. Flow Boiling Heat Transfer in Vertical Tubes Correlated by an Asymptotic Model. Heat Transfer Engineering. 13/2, 43-69.

Stout, K.J., Sullivan, P.J., Dong, W.P., Mainsah, E., Luo, N., Zahouani, H., 1993. The development of methods for the characterisation of roughness in three dimensions. Publ. No. EUR 15178 EN.